The Global Space-based Inter-Calibration System (GSICS)

By M. Goldberg, G. Ohring, J. Butler, C. Cao, R. Datla, D. Doelling, V. Gärtner, T. Hewison, B. Iacovazzi, D. Kim, T. Kurino, J. Lafeuille, P. Minnis, D. Renaut, J. Schmetz, D. Tobin, L. Wang, F. Weng, X. Wu, F. Yu, P. Zhang and T. Zhu.

AFFILIATIONS: GOLDBERG, OHRING, CAO, IACOVAZZI, WANG, WENG, WU, YU, AND ZHU–NOAA/NESDIS, CAMP SPRINGS, MARYLAND; BUTLER–NASA/GSFC, GREENBELT, MARYLAND; DATLA–NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, GAITHERSBURG, MARYLAND; DOELLING AND MINNIS–NASA/LaRC, HAMPTON, VIRGINIA; GÄRTNER–EUROPEAN SPACE AGENCY, DARMSTADT, GERMANY; KIM–KOREA METEOROLOGICAL ADMINISTRATION, SEOUL, SOUTH KOREA; KURINO–JAPAN METEOROLOGICAL AGENCY, TOKYO, JAPAN; LAFEUILLE–WMO, GENEVA, SWITZERLAND; RENAUT–CENTRE NATIONAL D'ETUDES SPATIALES, PARIS, FRANCE; HEWISON AND SCHMETZ–EUROPEAN ORGANIZATION FOR THE EXPLOITATION OF METEOROLOGICAL SATELLITES, DARMSTADT, GERMANY; TOBIN–UNIVERSITY OF WISCONSIN, MADISON, WISCONSIN; ZHANG–CHINA METEOROLOGICAL ADMINISTRATION, BEIJING, CHINA

ABSTRACT

The Global Space-based Inter-Calibration System (GSICS) is a new international program to assure the comparability of satellite measurements taken at different times and locations by different instruments operated by different satellite agencies. Sponsored by the World Meteorological Organization and the Coordination Group for Meteorological Satellites, GSICS will inter-calibrate the instruments of the international constellation of operational low-earth-orbiting (LEO) and geostationary (GEO) environmental satellites and tie these to common reference standards. The inter-comparability of the observations will result in more accurate measurements for assimilation in numerical weather prediction models, construction of more reliable climate data records, and progress towards achieving the societal goals of the Global Earth Observation System of Systems. GSICS includes globally coordinated activities for pre-launch instrument characterization, on-board routine calibration, sensor inter-comparison of near-simultaneous observations of individual scenes or overlapping time series, vicarious calibration using Earth-based or celestial references, and field campaigns. An initial strategy uses high accuracy satellite instruments, such as the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and Atmospheric Infrared Sounder (AIRS), and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) – Centre National d'Etudes Spatiales (CNES) Infrared Atmospheric Sounding Interferometer (IASI), as space-based reference standards for inter-calibrating the operational satellite sensors. Inter-calibration results obtained thus far are summarized and future plans are presented. Agencies participating in the program include Centre National d'Etudes Spatiales, China Meteorological Administration,

EUMETSAT, Japan Meteorological Agency, Korea Meteorological Administration, NASA, National Institute of Standards and Technology, and NOAA.

There is an increasing demand for improved calibration accuracy of satellite instrument radiances in response to such issues as interoperability within the Global Earth Observation System of Systems (GEOSS), data assimilation in numerical weather prediction (NWP), and climate change detection. For example, as NWP models become more reliable, their appetite for more accurate data input steadily grows. As the requirements for monitoring global climate become clearer (Ohring et al., 2005) – temperature changes as tiny as a few tenths of a degree per decade, ozone trends as small as 1% per decade – the measurements become more demanding.

Calibration is the process of quantitatively defining the satellite sensor responses to known signal inputs that are traceable to established standards (preferably International System Units or SI units). This allows measurement of absolute radiances in earth observations. By comparison, validation is the process of assessing, by independent means, the quality of the data products derived from the measured radiances. Calibrated radiances are the fundamental building blocks for all satellite products, including the radiances for data assimilation in NWP and fundamental climate data records. The quality of calibration directly affects the fidelity of satellite measurements as well as derived satellite products.

Calibration is required for the life cycle of the instrument. Prior to launch, instruments are calibrated in laboratories against known sources of radiant energy or other standards maintained at the national laboratories such as the National Institute of Standards and Technology (NIST) in the U.S. Pre-launch calibration is critical to instrument performance because it verifies the radiometric performance of on-board calibrators, determines filter in-band and out-of-band spectral response, detector linearity, stray light, instrument thermal response, and other performance attributes that are difficult to determine and correct post launch. Unfortunately, pre-launch calibrations may become invalid post launch because of suboptimal pre-launch characterization, changes during launch, and degradation on-orbit.

Post-launch calibration often relies on onboard calibration targets, such as blackbodies in the infrared and microwave, and solar diffusers or lamps in the UV/visible/near infrared. For those instruments without on-board calibrators, e.g., visible and near infrared imagers on most operational satellites, changes from pre-flight calibration can be monitored by viewing relatively stable Earth targets, such as deserts, Antarctic plateau snow cover, deep convective clouds, the Sun, Moon, and stars. Also valuable to the process of instrument calibration are special calibration sites, such as those of the Department of Energy's (DoE's) Atmospheric Radiation Measurement (ARM) program; aircraft underflight campaigns; highly accurate radiosonde and ozonesonde measurements; and other in-situ data bases.

Inter-calibration of satellite instruments involves relating the measurements of one instrument to those of another with a stated uncertainty. Instruments can be inter-calibrated when they are viewing the same scenes at the same times from the same viewing angles. Or, for satellite time series data in an archive, the overlapping records of two satellite instruments can be compared after a number of effects such as diurnal cycle are taken into account. Inter-calibration allows us to achieve relative consistency among satellites and remove biases between them. However, inter-satellite calibration without traceability to stable standards is subject to drift over time, and such drifts may obscure the climate trend over several decades. Therefore, calibration traceability to the international system of units (SI) is highly desirable.

The concept and strategy for a Global Space-Based Inter-Calibration System (GSICS) were submitted by the World Meteorological Organization (WMO) and endorsed by the Coordination Group for Meteorological Satellites (CGMS) in 2005. The overarching goal of GSICS is to ensure the comparability of satellite measurements taken at different times and locations by different instruments operated by different satellite agencies, and then tie the measurements to SI units. The operational objectives of GSICS are to:

- Ensure that instruments meet specification, pre-launch tests are traceable to SI standards, and the on-orbit satellite instrument observations are well calibrated by means of careful analysis of instrument performance, satellite inter-calibration, and validation with reference sites;
- Improve the use of space-based global observations for weather, climate and environmental applications through inter-calibration of the space component of the WMO's Global Observing System (GOS) and Global Earth Observations System of Systems (GEOSS); and
- Provide for the ability to re-calibrate archived satellite data using GSICS procedures to enable the creation of stable long-term climate data sets.

The GSICS program builds on concepts pioneered in the World Climate Research Program's (WCRP's) International Satellite Climatology Project (ISCCP) (Brest et al., 1997) and by several individual research groups. Efforts to intercalibrate geostationary and polar orbiting satellite radiance observations have been pursued for many years. Menzel et al. (1981), for example, used NOAA-6 High-Resolution Infrared Sounder (HIRS) observations to assess the radiometric calibration of the Visible IR spin-scan radiometer Atmospheric Sounder (VAS), the first sounding instrument in geostationary orbit, in the early 1980's. Several research groups within universities and government agencies have subsequently performed various satellite radiance and reflectance inter-calibrations on a routine basis. The need to provide timely cloud and radiation properties to the DOE ARM Program necessitated satellite intercalibrations (Minnis et al., 1995) that evolved into an ongoing intercalibration program at NASA Langley Research Center (LaRC) to support near-real time satellite cloud property retrievals (Minnis et al., 2008a) and the NASA Clouds and the Earth's Radiant Energy System (CERES) Program (Minnis et al., 2002a,b; Doelling et al., 2006). Efforts to inter-calibrate the operational satellites were further stimulated by the 1997 CGMS action for its member agencies to commence satellite intercalibration activities. This led to a number of studies at individual agencies (see, for example, König et al, 1999, Cao and Heidinger, 2002, Gunshor et al., 2004, and an entire list of key calibration publications at http://www.eumetsat.int/Home/Main/AboutEUMETSAT/InternationalRelations/CGMS/CGMSPublications/) Agencies currently participating in the GSICS program include Centre National d'Etudes Spatiales (CNES), China Meteorological Administration

(CMA), EUMETSAT, Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), NASA, National Institute of Standards and Technology (NIST), and NOAA.

COMPONENTS OF GSICS

The major components of GSICS are the: GSICS Executive Panel, GSICS Coordination Center (GCC), GSICS Processing and Research Centers (GPRCs), GSICS Research Working Group (GRWG), GSICS Data Working Group (GDWG), and Calibration Support Segments (CSS). The relationship of GSICS with the WMO Global Observing System, and the GSICS organizational structure are shown in Fig. 1.

The GSICS Executive Panel, consisting of representatives of the participating agencies, sets strategic priorities and monitors and evaluates the evolution and operations of the GSICS.

The GSICS Coordination Center, located at the NOAA National Environmental Satellite Data and Information Service (NESDIS) facility in Maryland, U.S., coordinates development of: methodologies, technical specifications, and criteria for satellite instrument inter-comparisons and associated software tools; data exchange formats and reporting times; and archiving strategies for collocated data and inter-calibration results. For this purpose, GCC personnel work closely with scientists and data managers from the GRWG and GDWG. The GCC is also the main communication hub for GSICS. The GCC archives, distributes, and responds to requests for GSICS calibration information, including all relevant data and results obtained by the program. The GCC also designs and hosts the central GSICS web site and a collaborative data server, and is responsible for publishing the *GSICS Quarterly* newsletter.

The GSICS Processing and Research Centers, one at each operational satellite agency, are responsible for pre-launch calibration, inter-calibration of their own agency's sensors with other satellite sensors, and supporting research activities.

The GSICS Research and Data Working Groups coordinate, plan and implement GSICS research and data management activities, developing methodologies for satellite instrument inter-comparisons, formats and specifications for data archives, and associated software tools. They also define technical specifications and criteria for satellite-to-satellite or satellite-to-reference sites collocation or overlap – e.g., viewing angle, temporal or horizontal window, and sampling frequency. The GRWG consists of scientists, and the GDWG of data management experts, representing the participating agencies.

GSICS Calibration Support Segments are relevant on-going or collaborative activities at various institutions that GSICS leverages to enhance its program. These calibration support activities are conducted at satellite agencies, national standards laboratories, major NWP centers, national research laboratories, and universities, and include:

- Performing in-situ observations at Earth reference targets (e.g., stable desert and perpetual snow areas), long-term specially equipped ground sites, and special aircraft and field campaigns to monitor satellite instrument performance;
- Observing stable extra-terrestrial calibration sources, such as the Sun, Moon, and stars, for on-orbit monitoring of instrument calibration;
- Comparing radiances computed from NWP analyses of atmospheric conditions with those observed by satellite instruments;
- Championing and supporting benchmark missions of the highest accuracy to serve as calibration standards in space for nailing down the calibration of the operational sensors;
- Developing calibration "best-practices" procedures; and
- Supporting efforts to make satellite instruments SI-traceable.

IMPLEMENTATION

GSICS is initially focusing on inter-calibrating current operational satellite data. Three initial scientific priorities have been identified: development of a GSICS Virtual Library, on-orbit inter-calibration and verification of operational satellite observations, and development of satellite instrument calibration science and standards (WMO, 2006a).

The GSICS Virtual Library will contain data and model output associated with satellite instrument cal/val opportunities and analyses, product documentation, meeting announcements and minutes, and general program information. It will be logically structured, easy to use, and readily accessible to GSICS partners and the user community.

The overarching goal of GSICS is to achieve inter-comparability of operational satellites. The GSICS program has selected reference sensors that have relatively high spectral resolution and accuracy to serve as on-orbit calibration standards for operational satellite instruments. These include the NASA Earth Observing System (EOS) *Aqua* Atmospheric Infrared Sounder (AIRS) and the EUMETSAT – CNES *Metop* Infrared Atmospheric Sounding Interferometer (IASI) as references for IR instruments, and the NASA EOS Moderate Resolution Imaging Spectroradiometer (MODIS) as a reference for solar reflectance instruments. The IASI is of particular value since it is an operational instrument and copies will be flown on *Metop-B* and *-C*. When true benchmark instruments (e.g., Climate Absolute Radiance and Refractivity Observatory (CLARREO), Holz et al., 2007) that cover the Earth's emission and reflectance spectrum are launched into space, they can be used as the reference instruments for GSICS inter-calibrations. Currently, GSICS performs low-earth-orbit (LEO)/geostationary-orbit (GEO), and LEO/LEO, instrumental measurements, and conducts an on-going program to develop and implement inter-comparison methodologies. Each GPRC is performing intercalibration of its own geostationary satellite against reference LEO instruments using a common algorithm baseline. Partnerships are being formed with institutions to carry out satellite radiance validation and calibration based on lunar and stellar irradiance measurements; observations of stable surface areas such as deserts; field site and airborne instrument in-situ measurements; and radiative transfer modeling based on NWP model and in-situ sounding data.

GSICS will advance satellite instrument calibration science and standards by: development of calibration and inter-calibration best practices; collaboration with national standards laboratories to perform calibration tests of instrument components to develop a model for sensor performance; conducting end-to-end system level measurements based on SI-traceable standards to validate the sensor performance model; creation of technology transportable to sensor test sites to perform SI-traceable measurements; and radiometric characterization of extraterrestrial sources such as the Sun, Moon and stars as stable sources of radiant energy to calibrate or monitor the stability of on-orbit optical sensors.

THE GSICS CORRECTION

GSICS will provide coefficients to the user community to adjust satellite observations to a common reference. The first major deliverable is the GSICS correction algorithm for the geostationary infrared imagers. The correction adjusts the geostationary data to be consistent with IASI and AIRS. The user simply applies the correction to the original data using GSICS supplied software and coefficients. The coefficients will be a function of channel and time and will have the form $R_C = a_0 + a_1 R_O$ where R_C is the corrected radiance, a_0 and a_1 are the coefficients, and R_O is the observed radiance. The coefficients for the geostationary imagers are derived from their collocations with IASI/AIRS.

GSICS will work with the user community to integrate the GSICS Correction into weather and climate operations, and research projects, and assess the impacts of the improved observations. The detailed specifications of GSICS deliverables will evolve in consultation with representative user groups.

INITIAL RESULTS FROM GSICS

The GSICS Research Working Group has developed the following phased implementation of inter-calibrations: 1) LEO/LEO solar reflective, IR, and microwave instruments, 2) GEO/LEO IR instruments, and 3) GEO/LEO solar reflectance instruments and GEO solar reflectance calibration monitoring. Initial emphasis will be placed on calibrating the operational sensors against in-flight reference instruments. Several GSICS Calibration Support Segment activities are also contributing to the GSICS program, including the development of calibration best practices and the conduct of aircraft underflights to check on the calibration of satellite sensors. .

LEO/LEO IR, microwave, and solar reflectance inter-calibrations. In the past few years, estimation of post-launch inter-satellite calibration-related radiance biases between similar LEO satellite instruments has been improved substantially with the further development of the Simultaneous Nadir Overpass/Simultaneous Conical Overpass (SNO/SCO) methods by NOAA (e.g., Cao et al., 2004, Cao et al., 2005a, 2005b, 2008). The essence of the SNO/SCO method is that similar space-borne radiometers flown on different LEO satellites at different altitudes periodically observe the same earth scene at nearly the same time and viewing angle, which significantly reduces uncertainties in the inter-calibration (see Fig. 2). The SNO/SCO method has been applied operationally to visible/near-infrared, infrared, and microwave radiometers on NOAA, EUMETSAT, and

NASA polar-orbiting satellites with excellent results. The GSICS program has assigned NOAA the responsibility to perform LEO/LEO IR instrument inter-calibrations for all operational satellites. A similar method developed at NASA, the Nearly Simultaneous Matched Radiance (NSMR) technique, cross-calibrates two different satellite sensors by regression fits to radiances matched in time, space, and viewing and illumination angles to within specified tolerances. It uses data from all viewing angles as long as they fall within the constraints. This method has also been successfully used to intercalibrate NOAA LEO, the Second Along-Track Scanning Radiometer (ATSR-2), the Tropical Rainfall Measuring Mission (TRMM) Visible InfraRed Scanner (VIRS), and the Aqua and Terra MODIS instruments (Doelling et al., 2001; Minnis et al., 2002a, 2002b, and 2008c). It will provide an independent assessment of the SNO/SCO results.

Figure 3 is an example of using AIRS to calibrate an operational NOAA Polar-orbiting Operational Environmental Satellite (POES) HIRS instrument using the SNO technique (Wang et al., 2007a). The AIRS hyperspectral measurements have been convolved to match the broad-band measurements of HIRS channel 5. The upper-left panel shows the bias of HIRS channel 5 relative to AIRS as a function of scene brightness temperature. Since this HIRS sounding channel is located at the slope region of the atmospheric spectra (shown in lower panel), a small error of the spectral response function (SRF) can cause biases in observed radiances. Such a scene temperature dependent bias suggests a miss-characterized SRF for the HIRS channel. Correcting for this mischaracterization by reconvolving the AIRS observations with a SRF shifted by 0.2 cm^{-1} yields the result in the upper-right panel of Fig. 3, which shows only a relatively constant average bias of about -0.1 K.

The results of applying the Simultaneous Conical Overpass (SCO) method to the microwave observations of rain-free tropical ocean areas by a series of SSM/I instruments on Defense Meteorological Satellite Program (DMSP) satellites since 1987 are shown in Figure 4. Collocated SSM/I measurements from a pair of satellites are obtained when they simultaneously pass over a local area. The bias between the SCO pairs is characterized over various surface conditions, relative to the F13 satellite, which had the longest record. If there is no direct collocation between F13 and a satellite, a third satellite which intercepts with F13 is used as a transfer radiometer. This cascading approach is applied for all SSM/I sensors from F10, F11, F13, F14, and F-15 satellites during 1992-2006. SSM/I measures the microwave radiance at four frequencies (19.35, 22.235, 37 and 85.5 GHz) with dual polarization (except for 22.235 GHz, which has only vertical polarization). Fig. 4 compares the time series of rain-free monthly mean brightness temperature over the tropical oceanic (20°S-20°N) areas before and after intersensor calibration for three of the SSM/I channels. The graphs clearly demonstrate that the inter-calibration reduces the sensor to sensor biases and results in more consistent trends in brightness temperature.

As noted earlier, a key objective of GSICS is to apply the improved calibrated radiances to derive important geophysical parameters for monitoring climate change. For example, the total precipitable water (TPW) can be obtained from the intercalibrated brightness temperatures of the three channels shown in Fig. 4 using the following equation (Alishouse et al., 1990).

$$TPW = 232.894 - 0.149T_b(19V) - 1.829T_b(22V) - 0.370T_b(37V) + 0.0062[T_b(22V)]^2$$

,

where $T_b(19V)$, $T_b(37V)$, and $T_b(22V)$ are the microwave brightness temperatures for the vertical polarization 19.35, 37, and 22.235, GHz channels, respectively. We compute a decadal trend for rain-free tropical oceans of 0.63 mm/decade, or about 1.4% per decade. This trend is consistent with other independent TPW trends derived from the SSM/I observations (Mears et al., 2007). It should be noted that without the SSM/I intersensor adjustments the computed trend is an erroneous 1.35 mm per decade – a factor of two greater than the derived trend – demonstrating the importance of inter-calibration.

Figure 5 shows an example of using MODIS to calibrate the visible channel of a NOAA Advanced Very High Resolution Radiometer (AVHRR) at SNO intersections. This figure shows a three year time series of the ratio of *Aqua* MODIS to *NOAA-18* operationally calibrated AVHRR. The results indicate that the operationally calibrated AVHRR reflectance values underestimate the albedos by about 10 % (relative to MODIS). This is relatively large error. For example, if the visible reflectance is used to estimate the planetary albedo, an absolute error of about 3 % would result, a value that would more than offset a doubling of CO_2.

LEO/GEO IR instrument calibrations. Many GSICS members have contributed to the baseline algorithm for GSICS GEO/LEO IR instrument inter-calibration, which uses the AIRS and IASI hyperspectral instruments as references (e.g., Wang et al., 2009b). It incorporates the gap-filling algorithm developed by JMA (Tahara and Kato, 2009) that is critical in using AIRS data. The algorithm collocates GEO and LEO data in time (within 5 minutes), viewing geometry (difference in optical path of the two satellites less than 1%), and space (accurate to both instruments' geolocation uncertainty). It then spatially averages the GEO pixels within each LEO pixel and spectrally convolves the LEO hyperspectral radiances with GEO's SRF. These results, as well as all the original measurements and ancillary data (e.g., collocation uniformity and relative azimuth angle) that may be used in the data selection step, are archived in NetCDF4 format. This algorithm has been implemented operationally at NOAA for GOES Imager IR data, at JMA for MTSAT Imager IR data, and experimentally at KMA using MTSAT in preparation for Korea's Communication, Ocean and Meteorological Satellite (COMS) Program.

An example of the application of this method is shown in Fig. 6, which compares (upper panel) the GOES 13.3 μm channel to both AIRS and IASI (Wang et al., 2009b). The jumps on July 2, 2008 and January 2, 2009 are due to a decontamination procedure that was applied to the GOES Imager. Differences between AIRS and IASI, obtained by a double-differencing technique, with GOES as the transfer radiometer, are shown. The difference between AIRS and IASI is small and stable despite the fact that their differences from GOES are large and variable. The lower panel of Fig. 6 illustrates the elimination of the GOES bias error resulting from the decontaminations by applying the GSICS Correction procedure, which is based on the differences between GOES and AIRS shown in the upper panel of the figure. The lower panel shows the difference between observed brightness temperatures and brightness temperatures computed using a radiative transfer model and the NCEP analysis atmospheric state parameters for GOES-12 channel 6, before and after the correction, respectively. The bias is reduced from 3 K to nearly zero, a significant improvement for both weather and climate users.

EUMETSAT has implemented an extended version of the baseline methodology to inter-compare LEO IASI hyperspectral observations with GEO *Meteosat Second Generation* (*MSG*) Spinning Enhanced Visible and Infrared Imager (SEVIRI) imager measurements. In this method, the mean and variance of the radiances in the 25 Meteosat pixels closest to each IASI Instantaneous Field of View (IFOV) are calculated. This is repeated for all IASI pixels within ±30° latitude/longitude of the geostationary sub-satellite point where the instruments' view angles are within 2°. A weighted linear regression is then calculated between the IASI and SEVIRI radiances, accounting for the variance of the scene. This is used to estimate the mean difference between the instruments' radiances for a reference scene, which finally is converted to a brightness temperature (*Tb*). Table 1 shows the mean brightness temperature difference between IASI and SEVIRI at different wavelengths for the year 2007. The clear sky reference scene *Tb*s are typical values within the domain of the inter-comparisons. This inter-comparison indicates that the biases are small – less than 0.6 K – for all the channels except for 13.4 μm, for which the bias is -1.6 K. Four of the nine SEVIRI channels have an extremely low bias – less than 0.05 K.

The GSICS program has assigned responsibility for operational LEO/GEO IR instrument inter-calibrations as shown in Table 2. The *Aqua* AIRS and *Metop* IASI LEO instruments will serve as reference standards for the GEO IR measurements. These calibrations will be assessed using the NSMR method between both GEO and LEO (Minnis et al., 2002b) and between GEO and GEO satellites (Minnis, 1989).

LEO/GEO solar reflectance instruments inter-calibrations and GEO solar reflectance calibration monitoring. The GSICS Research Working Group has developed a roadmap for inter-calibrating solar reflectance instruments on LEO and GEO satellites and monitoring GEO solar reflectance measurements. Participating GSICS Processing and Research Centers will perform these activities as shown in Table 3. NASA LaRC will continue inter-calibrating all the GEO satellites, using MODIS as a reference instrument for the NSMR method (Minnis et al., 2002a). It will also monitor sensor degradation using the Deep Convective Cloud (DCC) technique (Doelling et al., 2004; Minnis et al, 2008c). A DCC is defined as a cold and bright tropopause target near the equator. These targets provide maximum earth-view radiances in the solar reflective bands, and have reflection and absorption components that are in equilibrium, thereby maintaining a constant albedo at the top of the atmosphere. Collectively, these near isotropic and predictable albedos can be used to detect the relative gain drift of a visible sensor, although they cannot be used to provide absolute calibration. A comparison of results from the LEO/GEO intercalibration and DCC degradation monitoring techniques is shown in Fig. 7. The figure shows good agreement of the GOES-8 visible channel degradation rates obtained with the DCC technique and the LEO/GEO inter-calibration method, in which the well-calibrated Visible Infrared Scanner (VIRS) on the Tropical Rainfall Measuring Mission (TRMM) is used as the reference instrument.

CNES has evolved systems for monitoring LEO solar reflectance instruments using natural calibration targets and will focus on this activity for GSICS. CNES systematically collects satellite observations of 19 desert sites in North Africa and Saudi Arabia, as well as ocean and snow surfaces. The data are stored in its Systeme d'analyse des defaillances en exploitation (SADE) – i.e., system for analysis of failures in service – data base. Results from this method are illustrated in Fig. 8, which shows a time series of the ratio of the calibrated reflectance of the MODIS to the European Space Agency (ESA) Medium Resolution Imaging Spectrometer (MERIS) instrument for the 0.665 µm visible channel from the 19 desert sites. Note the excellent agreement and stability between the two sensors. This is a very important result because it provides very strong justification for GSICS to use MODIS as a reference instrument for visible inter-calibration. MODIS is used instead of MERIS because it has better temporal and spatial coverage.

Calibration Support Segment (CSS) activities. One of the CSSs involves the use of well-calibrated instruments on aircraft to underfly satellite sensors. The University of Wisconsin has underflown IASI with high spectral resolution infrared spectro-radiometers: the Scanning High-resolution Interferometer Sounder (S-HIS) and the

National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed-Interferometer (NAST-I). Coincident with the satellite overpasses, the S-HIS and NAST-I observations provide NIST-traceable validation of the on-orbit satellite observations. A sample result for a portion of the IASI shortwave band for clear sky conditions over the ARM site in north central Oklahoma is shown in Fig. 9. The analysis shows that the IASI absolute calibration is accurate to 0.1 to 0.2 K. Similar results have been obtained for AIRS for past and recent flights. Details of the analyses techniques and more results are available in the literature (e.g. Larar et al., 2003, Tobin et al., 2006).

The China Meteorological Administration has established four ground-based reference sites for the purpose of calibrating satellite sensors. These sites, their locations, and calibration objective are shown in Table 4.

DISSEMINATION OF CALIBRATION RESULTS

The main GSICS data and information storage and distribution facility is located at the GSICS Coordination Centre (GCC) at NOAA. The GCC is responsible for maintaining pathways of information communication and data transfer among the GSICS partners and the user community. It serves as a one-stop source for information on all satellite instruments. The GCC provides easy, near real-time access to calibration information via its website. Collaborative data servers to be hosted by NOAA and EUMETSAT are to house the data produced by GSICS members. From time to time the GCC in consultation with GPRCs will issue special assessment reports of instrument trends or other results of general interest. The GCC will also communicate to satellite agencies GSICS guidance on satellite instrument calibration. To inform and unify the satellite calibration and user community, the GCC publishes and distributes an electronic GSICS Quarterly Newsletter with news and notes on satellite calibration activities throughout the world.

The GSICS web site is located at http://gsics.wmo.int/. Future plans of the GCC are to expand the storage and dissemination of GSICS data and information by establishing a GSICS Virtual Library. The proposed Virtual Library is envisioned to have many services similar to the National Physical Laboratory's implementation of *Second Life* and the Virtual Center for Decadal Climate Variability (Mehta et al, 2006).

BENEFITS

The improved calibration and inter-calibration of operational satellite sensors resulting from GSICS is designed to lead to more accurate sensor observations and instrument-to-instrument measurement inter-comparability. Benefits will be realized in applications of satellite data to weather prediction, assessing global climate change, testing climate model predictions, and achieving the societal goals of the Global Earth Observation System of Systems (GEOSS).

The WMO plans to make use of GSICS results at its recently initiated global network of **S**ustained, **C**o-**O**rdinated **P**rocessing of **E**nvironmental Satellite Data for **C**limate **M**onitoring (SCOPE-CM) as shown in Fig. 10. The overall objective of these Centers is the continuous and sustained provision of high-quality Essential Climate Variables satellite products on a global scale, which are specified in the Global Climate Observing System (GCOS) Implementation Plan (WMO, 2006b).

SUMMARY AND FUTURE PLANS

The Global Space-based Inter-Calibration System (GSICS) is off to a good start toward achieving its overarching goal of ensuring the comparability of satellite measurements taken at different times, by different instruments, operated by different agencies, and tying these measurements to the international system of units (SI). Eight international agencies are already participating in this program of the WMO and the Coordination Group for Meteorological Satellites.

The GSICS infrastructure is in place: the GSICS Coordination Center (GCC) infrastructure to coordinate the inter-calibration activities, archive and disseminate results, and operate the GSICS website; the GSICS Processing and Research Centers (GPRCs), responsible for pre-launch calibration, inter-calibration of their own agency's sensors with other satellite sensors, and supporting research activities; the GSICS Research Working Group (GRWG) and GSICS Data Working Group (GDWG) to assist in the coordination, planning and implementation of GSICS research and data management activities; and the Calibration Support Segments, which are leveraged on-going or collaborative relevant activities at other institutions, to enhance the GSICS program.

An initial GSICS strategy is the use of selected reference sensors that have relatively high spectral resolution and accuracy to serve as in-orbit calibration standards for operational satellite instruments. Reference instruments include the NASA EOS AIRS and the EUMETSAT – CNES *MetOp* IASI for IR sensors, and the NASA EOS MODIS for solar reflectance measurements. Once benchmark instruments covering the Earth's emission and reflectance spectrum, e.g., Climate Absolute Radiance and Refractivity Observatory (CLARREO) (Anderson et al., 2008; see http://clarreo.larc.nasa.gov/), are in space, they can be used as the reference instruments for GSICS inter-calibrations.

Aside from satellite-to-satellite instrument inter-calibrations, GSICS is also applying other tools supplied by its Calibration Support Segments. These comprise satellite radiance validation and calibration based on lunar and stellar irradiance measurements; observations of stable surface areas such as deserts, Antarctic plateau snow cover, deep convective clouds, and ocean areas; comparisons with field site and airborne instrument in-situ measurements; and radiative transfer modeling based on NWP model and in-situ sounding data.

Examples of initial results include: application of the Simultaneous Nadir Overpass/Simultaneous Conical Overpass (SNO/SCO) techniques to inter-compare similar NOAA POES, EUMETSAT *MeTop-A*, and NASA *Aqua* instruments; inter-calibration of GOES and MTSAT Imager IR data with AIRS and IASI, and EUMETSAT Meteosat-9 SEVIRI IR channels with the EUMETSAT – CNES *Metop* IASI; monitoring the degradation of the Meteosat-8 visible channel using the Deep Convective Cloud method; checking the calibration of the ESA ENVISAT MERIS instrument using natural targets over the ocean; and validation of the IASI calibration with measurements from the S-HIS on high-altitude aircraft under-flights.

Future plans include establishing closer ties with the climate and NWP communities. GSICS plans to recalibrate historical instrument records and work with the climate community to generate climate data records. GSICS also intends to engage the NWP centers in the evaluation of the impact of improved satellite calibration on weather forecasts. In summary, the GSICS program will provide stable, inter-calibrated, unbiased satellite observations that will improve weather prediction, facilitate detection of climate change, permit testing of climate model predictions, and help the Global Earth Observation System of Systems (GEOSS) to achieve its societal goals.

ACKNOWLEDGEMENTS

The contents of this paper are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of any U.S. government agency.

REFERENCES

Alishouse, J.C. S.A. Snyder, J. Vongsathorn, and R. R. Ferraro, 1990: Determination of oceanic total precipitable water from the SSM/I. *Trans. Geosci. Remote Sens.*, **28**, 811-816.

Anderson, D., K. W. Jucks, and D. F. Young, 2008: The NRC Decadal Survey Climate Absolute Radiance and Refractivity Observatory: NASA implementation. *2008 IEEE Intl. Geosci. & Remote Sens. Symp.*, Boston, MA, July 6-11, CD-ROM, 3 pp.

Brest, C.L., W.B. Rossow, and M. Roiter, 1997: Update of radiance calibrations for ISCCP. *J. Atmos. Ocean Tech.*, **14**, 1091-1109.

Cao, C., and A. Heidinger, 2002: Inter-Comparison of the Longwave Infrared Channels of MODIS and AVHRR/NOAA-16 using Simultaneous Nadir Observations at Orbit Intersections, Earth Observing Systems. *Proc. SPIE*, 4814, 306-316.

Cao, C., M. Weinreb, and H. Xu, 2004: Predicting simultaneous nadir overpasses among polar-orbiting meteorological satellites for the intersatellite calibration of radiometers. *J. Atmos. Oceanic Technol.*, **21**, 537-542

Cao, C., F. Weng, M. Goldberg, X. Wu, H. Xu, and P. Ciren, 2005a: Intersatellite calibration of polar-orbiting radiometers using the SNO/SCO method. Geoscience and Remote Sensing Symposium, *IGARSS Proceedings* Volume 1, doi:10.1109/IGARSS.2005.1526116.

Cao, C., H. Xu, J. Sullivan, L. McMillin, P. Ciren, and Y. Hou, 2005b: Intersatellite radiance biases for the High Resolution Infrared Radiation Sounders (HIRS) onboard NOAA-15, -16, and -17 from simultaneous nadir observations. *J. Atmos. Oceanic*

Technol, **22**, 381-395.

Cao C., X. Xiong, A. Wu, X. Wu, 2008: Assessing the consistency of AVHRR and MODIS L1B reflectance for generating Fundamental Climate Data Records. *J. Geophys. Res.,* **113**, D09114, doi:10.1029/2007JD009363.

Doelling, D. R., V. Chakrapani, P. Minnis, and L. Nguyen, 2001: The calibration of NOAA-AVHRR visible radiances with VIRS. *Proc. AMS 11th Conf. Satellite Meteorology and Oceanography*, Madison, WI, Oct. 15-18, 614-617.

Doelling, D. R., L. Nguyen, and P. Minnis, 2004: On the use of deep convective clouds to calibrate AVHRR data. *Proc. SPIE 49th Ann. Mtg., Earth Observing Systems IX Conf.*, Denver, CO, August 2-6, 5542, 281-289.

Doelling, D. R., D. F. Young, B. A. Wielicki, T. Wong, and D. F. Keyes, 2006: The newly released 5-year Terra-based monthly CERES radiative flux and cloud product. *Proc 12th AMS Conf. on Atmos. Rad.*, Madison, WI, July 10-15, 9.4, CD-ROM, 5 pp.

Gunshor, M. M., T. J. Schmit, and W. P. Menzel, 2004: Intercalibration of the infrared window and water vapor channels on operational geostationary environmental satellites using a single polar orbiting satellite. *J. Atmos. Oceanic Tech.*, **21**, 61-68.

König, M., J. Schmetz, and S. Tjemkes, 1999: Satellite Intercalibration of IR window radiance Observations. *Adv. Space. Res.*, **23**, 1341-1348

Larar, A. M., et al., 2003: Validation studies using NAST-I measurements from recent field campaigns. *Proc. SPIE.* 5157, 23-33.

Mears, C.A., B. D. Santer, F. J. Wentz, K. E. Taylor, and M. F. Wehner, 2007: Relationship between temperature and precipitable water changes over tropical oceans. *Geophysical Research Letters*, **34**, L24709, 10.1029/2007GL031936.

Mehta, V.M., E. J. Lindstrom, L. de Kort, and A. J. DeCandis, 2006: The Virtual Center for Decadal Climate Variability. *Bull. Amer. Meteor. Soc.*, **87**, 1223-1225.

Menzel, W. P., W. L. Smith, and L. D. Herman, 1981: Visible infrared spin-scan radiometer atmospheric sounder radiometric calibration: An inflight evaluation from intercomparisons with HIRS and radiosonde measurements. *Appl. Opt.*, **20**, 3641-3644.

Minnis, P., 1989: Viewing zenith angle dependence of cloudiness determined from coincident GOES East and GOES West data. *J. Geophys. Res.*, **94**, 2303-2320.

Minnis, P., D. R. Doelling, L. Nguyen, W. F. Miller, and V. Chakrapani, 2008c: Assessment of the visible channel calibrations of the TRMM VIRS and MODIS on *Aqua* and *Terra*. *J. Atmos. Oceanic Technol.*, **25**, 385-400.

Minnis, P., L. Nguyen, D. R. Doelling, D. F. Young, W. F. Miller, and D. P. Kratz, 2002a: Rapid calibration of operational and research meteorological satellite imagers, Part I: Evaluation of research satellite visible channels as references. *J. Atmos. Oceanic Technol.*, **19**, 1233-1249.

Minnis, P., L. Nguyen, D. R. Doelling, D. F. Young, W. F. Miller, and D. P. Kratz, 2002b: Rapid calibration of operational and research meteorological satellite imagers, Part II: Comparison of infrared channels. *J. Atmos. Oceanic Technol.*, **19**, 1250-1266.

Minnis, P., L. Nguyen, R. Palikonda, P. W. Heck, D. A. Spangenberg, D. R. Doelling, J. K. Ayers, W. L. Smith, Jr., M. M. Khaiyer, Q. Z. Trepte, L. A. Avey, F.-L. Chang, C. R. Yost, T. L. Chee, and S. Sun-Mack, 2008a: Near-real time cloud retrievals from operational and research meteorological satellites. *Proc. SPIE Europe Remote Sens. 2008*, Cardiff, Wales, UK, 15-18 September, 7107-2, CD-ROM, 8 pp.

Minnis, P., et al., 2008b: Cloud detection in non-polar regions for CERES using TRMM VIRS and Terra and Aqua MODIS data. *IEEE Trans. Geosci. Remote Sens.*, **46**, 3857-3884.

Minnis, P., W. L. Smith, Jr., D. P. Garber, J. K. Ayers, and D. R. Doelling, 1995: Cloud properties derived from GOES-7 for the Spring 1994 ARM Intensive Observing Period using Version 1.0.0 of the ARM satellite data analysis program. *NASA RP 1366*, 59 pp.

Ohring, G., B. Wielicki, R. Spencer, W.J. Emery, and R. Datla, 2005: Satellite instrument calibration for measuring global climate change: Report of a workshop. *Bull. Am. Met. Soc.*, **86**, 1303–1313.

Tahara, Y. and K. Kato, 2009: New Spectral Compensation Method for Intercalibration Using High Spectral Resolution Sounder, Japanese Meteorological Satellite Center Technical Note, No. 52.

Tobin, D., et al., 2006 : Radiometric and spectral validation of Atmospheric Infrared Sounder observations with the aircraft-based Scanning High-Resolution Interferometer Sounder. *J. Geophys. Res.,* **111**, D09S02, doi:10.1029/2005JD006094.

Wang, L., C. Cao, and P. Ciren, 2007: Assessing NOAA-16 HIRS Radiance Accuracy Using Simultaneous Nadir Overpass Observations from AIRS. *J. Atmos. Oceanic Technol.,* **24**, 1546-1561.

Wang, L., and C. Cao, 2008: On-orbit calibration assessment of AVHRR longwave channels on MetOp-A using IASI. *Trans. Geosci. Remote Sens.*, **46**, Issue 4005 – 4013, DOI:10.1109/TGRS.2008.2001062.

Wang L., C. Cao, and M. Goldberg, 2009a: Inter-calibration of GOES-11 and GOES-12 water vapor channels with MetOp/IASI hyperspectral measurements. *J. Atmos. Oceanic Technol.* (Accepted upon revision).

Wang, L., X. Wu, Y. Li, M. Goldberg, S.-H. Sohn, and C. Cao, 2009b: Comparison of AIRS and IASI radiances using GOES imagers as transfer radiometers toward climate data records. *J. Appl. Meteor. Climate* (To be submitted).

WMO, 2006a: Implementation Plan for a Global Space-Based Inter-Calibration System (GSICS), version 1, April 2006. World Meteorological Organization, 22 pp.

WMO, 2006b: Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, GCOS – 92 (WMO/TD No. 1219) (available through http://www.wmo.int/pages/prog/gcos/index.php)

Figure Captions

Fig. 1. GSICS within the WMO Global Observing System (upper panel) and the organizational structure of GSICS (lower panel).

Fig. 2. Satellite tracks crossing each other produce opportunities for Simultaneous Nadir Overpasses (SNOs).

Fig. 3. Brightness temperature biases between EOS AIRS-convolved HIRS and NOAA-16 HIRS channel 5 (centered at 716 cm^{-1}) data before (upper-left) and after (upper-right) the HIRS spectral response function is shifted 0.2 cm^{-1}. The plus symbols represent the Southern Hemisphere SNO data, while the triangles represent the Northern Hemisphere SNO data. The lower-panel shows the SRFs of HIRS channels 5, 6, and 7 and an AIRS spectrum.

Fig. 4. Time series of the SSM/I rain-free monthly mean brightness temperature (Tb) over tropical oceans at 19V GHz (top panel), 22V GHz (middle panel) and 37V GHz (bottom panel) channels before (left panel) and after (right panel) intersensor calibration.

Fig. 5. Time series of *NOAA-18* AVHRR to *Aqua* MODIS visible channel albedo ratio based on SNO events. Each data point includes the standard error bars for the 99% confidence interval.

Fig. 6. **Upper panel:** Time series of daytime Brightness Temperature (BT) differences between the GOES-12 13.3 μm channel and AIRS (red)/IASI (blue) from June 2007 to January 2009. The sudden bias changes after July 2007 and January 2009 are due to decontamination procedures applied to the GOES Imager (indicated by the gray dashed lines). The black dots represent the double difference (difference between GOES-AIRS and GOES-IASI) and suggest excellent agreement between AIRS and IASI. **Lower panel:** The difference between observed and calculated brightness temperatures for GOES-12 13.3 μm channel before and after the GSICS correction is applied. The GSICS correction is determined from the GOES- AIRS differences in the upper panel.

Fig. 7 Monitoring of the GOES-8 visible (0.63μm) channel using the DCC and LEO/GEO inter-calibration methods. The left panel (a) shows the GOES-8 visible gain during 1998 through 2003, based on the inter-calibration of VIRS and GOES-8. The right panel (b) shows the relative DCC calibration, normalized to the VIRS/GOES-8 gain on January 2001, based on the degradation of the DCC visible digital counts over time. A 2nd order regression is also plotted for each method. Note the excellent agreement between the two calibration methods.

Fig. 8. Time series of the ratio of the ESA MERIS to NASA MODIS 0.665 μm visible channel reflectance from observations at 19 desert sites in North Africa and Saudi Arabia. The results show very good agreement and stability between the two sensors.

.

Fig. 9. Validation of IASI observations for clear sky conditions using S-HIS and NAST-I observations from a high altitude aircraft underflight on 19 April 2007 over the Oklahoma ARM site. The top panel shows S-HIS (red), NAST-I (blue), and IASI (black) mean brightness temperature (BT) spectra reduced to S-HIS spectral resolution; the bottom panel shows IASI minus S-HIS (red) and IASI minus NAST-I (blue) differences, with maximum channel by channel differences on the order of 0.1 to 0.2 K.

Fig. 10. The role of GSICS in the end-to-end process of creating satellite-based climate data records operationally at the WMO's Regional/Specialized Satellite Centers (R/SSC) for Climate Monitoring from observations of the satellite component of the Global Observing System (GOS).

Table Captions

Table 1. Brightness temperatures, *Tbs*, for reference scenes and mean *Tb* difference between *Meteosat-9* (*MSG2*) SEVIRI and *Metop-A* IASI during 2007.

Table 2. The GSICS Processing and Research Centers responsibilities for GEO/LEO IR instrument inter-calibrations. The *Aqua* AIRS and *Metop* IASI LEO instruments will serve as reference standards for the GEO IR measurements.

Table 3. GPRC contributions to GEO/LEO solar reflectance measurement inter-calibrations and calibration monitoring.

Table 4. Ground-based reference sites established by the China Meteorological Administration for calibration of satellite sensors.

Table 1. Brightness temperatures, *Tbs*, for reference scenes and mean *Tb* difference between *Meteosat-9* (*MSG2*) SEVIRI and *Metop-A* IASI during 2007.

Ch (μm)	**Clear-sky Ref Scene (K)**	**Mean Bias MSG2-IASI (K)**	**Standard Deviation (K)**
3.9¶	290	0.17¶	0.10
6.2	240	0.61	0.05
7.3	260	0.25	0.04
8.7	290	0.02	0.04
9.7	270	0.00	0.07
10.8	290	0.03	0.06
12.0	290	0.05	0.06
13.4	270	-1.63	0.26

¶ IASI response is limited to wavenumbers below 2760 cm-1, which underestimates radiance of a 290 K scene in 3.9 μm channel by 0.17 K.

Table 2. The GSICS Processing and Research Centers responsibilities for GEO/LEO IR instrument inter-calibrations. The *Aqua* AIRS and *Metop* IASI LEO instruments will serve as reference standards for the GEO IR measurements.

GSICS Processing and Research Center	Satellites
NOAA/NESDIS	GOES, MSG/MTSAT/FY2
EUMETSAT	MSG (IASI only)
JMA	MTSAT
CMA	FY2C/D

Table 3. GPRC contributions to GEO/LEO solar reflectance measurement inter-calibrations and calibration monitoring.

	GSICS PROCESSING AND RESEARCH CENTER				
CALIBRATION SOURCE	*NASA/LaRC*	*JMA*	*EUMETSAT*	*NOAA/NESDIS*	*CNES*
MODIS	ALL GEO			GOES	
Deep Convective Clouds	ALL GEO		MSG	GOES	Parasol
Desert			MSG	GOES	All
Moon				GOES	
Radiative Transfer		MTSAT			
Sunglint				GOES	VGT, Parasol, MERIS
Star				GOES	

Table 4. Ground-based reference sites established by the China Meteorological Administration for calibration of satellite sensors.

Site	Characteristics	Location	Purpose
Dunhuang	Gobi Desert, homogeneous surface, dry atmosphere, and high visibility	40° 10’ N 94° 20’ E Elevation: 1176 m	On-orbit calibration of VNIR bands
Qinghai	Lake, good Lambertian feature, dry atmosphere, and high visibility	36° 45’ N 100° 20’ E Elevation: 3196 m	On-orbit calibration of TIR band
Beijing	Laboratory on top of building	39.92° N, 116.46° E Elevation: 48 m	Validation of radiative transfer calculations at very high spectral resolution, Benchmark measurements
Lijiang	Local meteorological observation station, dry atmosphere, high visibility	26.86° N, 100.25° E Elevation: 2300 m	Pre-launch calibration of VNIR band of engineering and flight model

1.

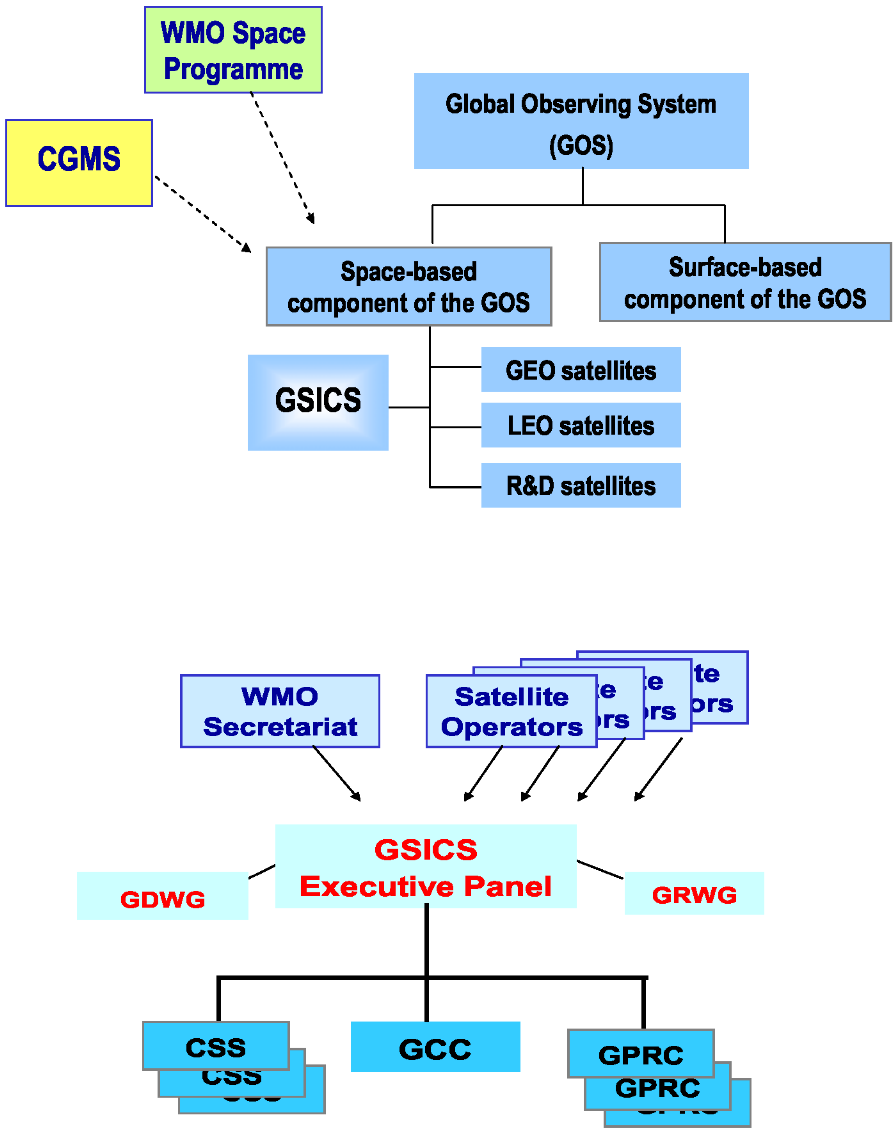

Fig. 1. GSICS within the WMO Global Observing System (upper panel) and the organizational structure of GSICS (lower panel).

2.

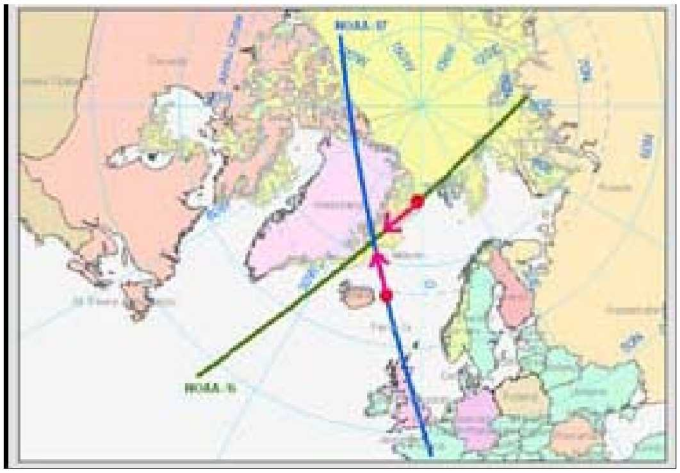

Fig. 2. Satellite tracks crossing each other produce opportunities for Simultaneous Nadir Overpasses (SNOs).

3.

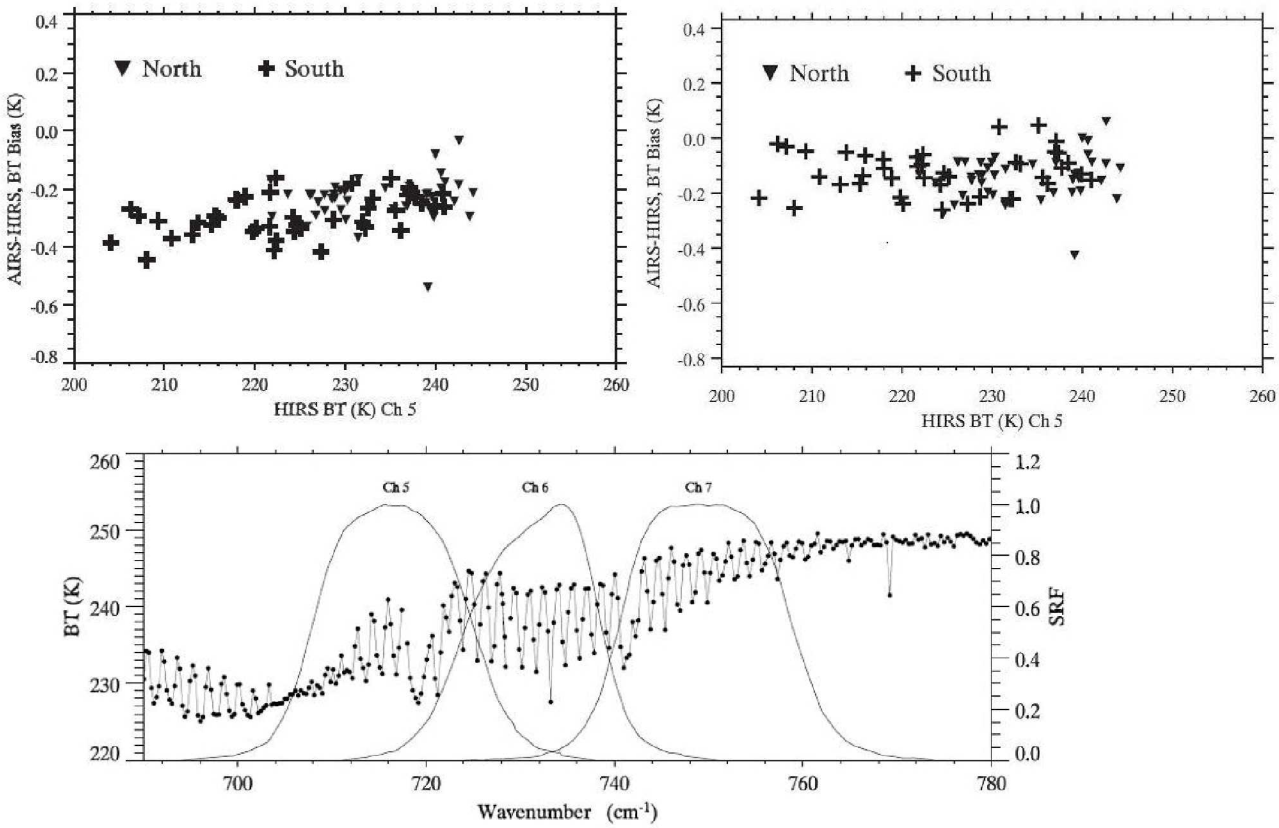

Fig. 3. Brightness temperature biases between EOS AIRS-convolved HIRS and NOAA-16 HIRS channel 5 (centered at 716 cm^{-1}) data before (upper-left) and after (upper-right) the HIRS spectral response function is shifted 0.2 cm^{-1}. The plus symbols represent the Southern Hemisphere SNO data, while the triangles represent the Northern Hemisphere SNO data. The lower-panel shows the SRFs of HIRS channels 5, 6, and 7 and an AIRS spectrum.

4.

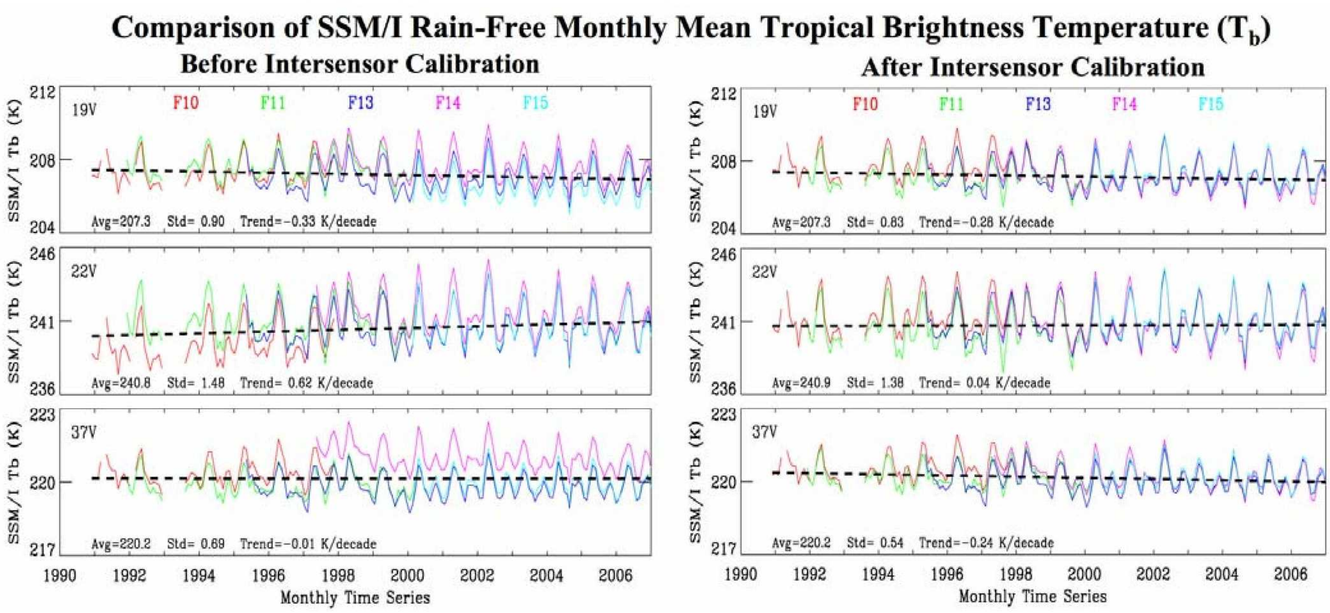

Fig. 4. Time series of the SSM/I rain-free monthly mean brightness temperature (Tb) over tropical oceans at 19V GHz (top panel), 22V GHz (middle panel) and 37V GHz (bottom panel) channels before (left panel) and after (right panel) intersensor calibration.

5.

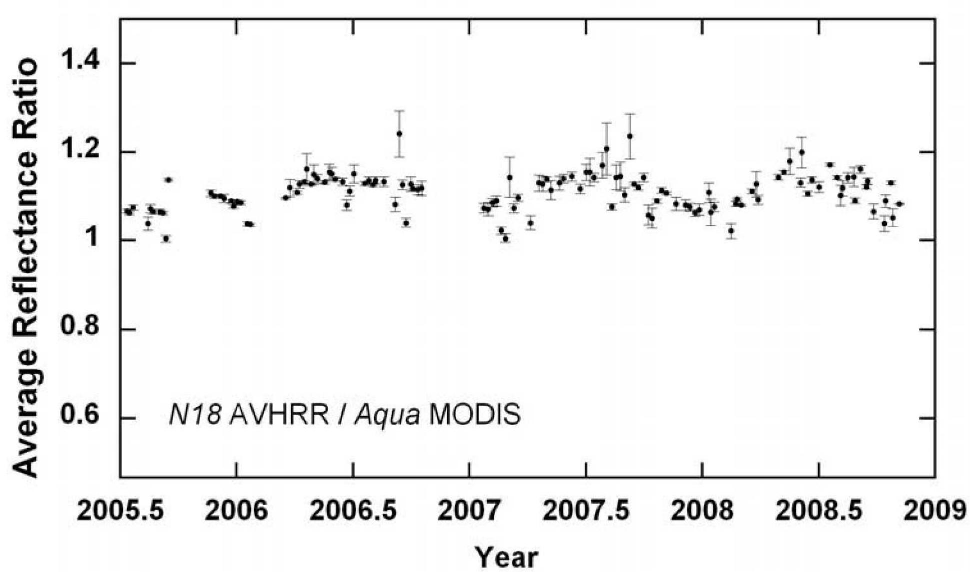

Fig. 5. Time series of *NOAA-18* AVHRR to *Aqua* MODIS visible channel albedo ratio based on SNO events. Each data point includes the standard error bars for the 99% confidence interval.

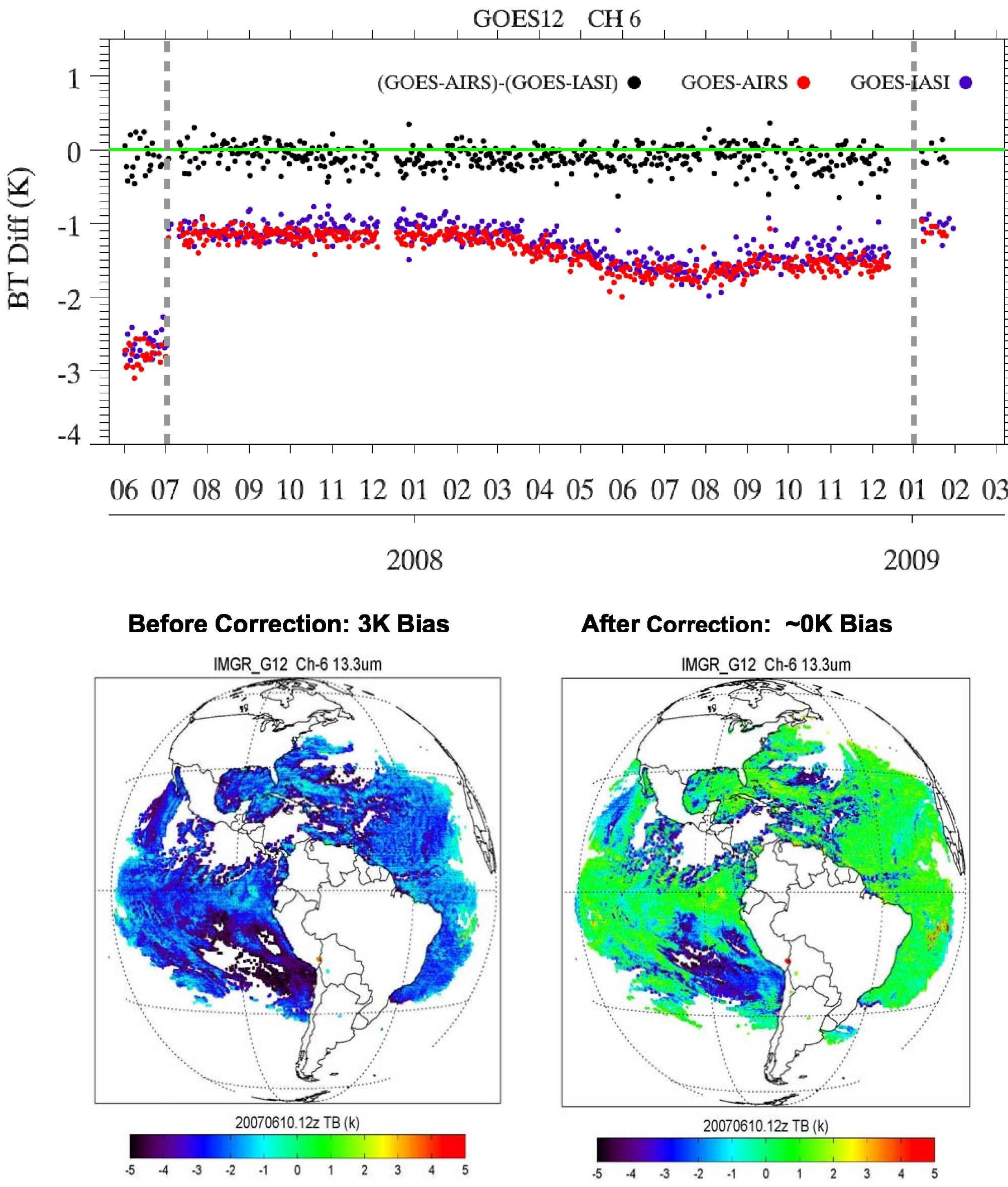

Fig. 6. **Upper panel:** Time series of daytime Brightness Temperature (BT) differences between the GOES-12 13.3 μm channel and AIRS (red)/IASI (blue) from June 2007 to January 2009. The sudden bias changes after July 2007 and January 2009 are due to decontamination procedures applied to the GOES Imager (indicated by the gray dashed lines). The black dots represent the double difference (difference between GOES-AIRS and GOES-IASI) and suggest excellent agreement between AIRS and IASI. **Lower panel:** The difference between observed and calculated brightness temperatures for GOES-12 13.3 μm channel before and after the GSICS correction is applied. The GSICS correction is determined from the GOES-AIRS differences in the upper panel.

7.

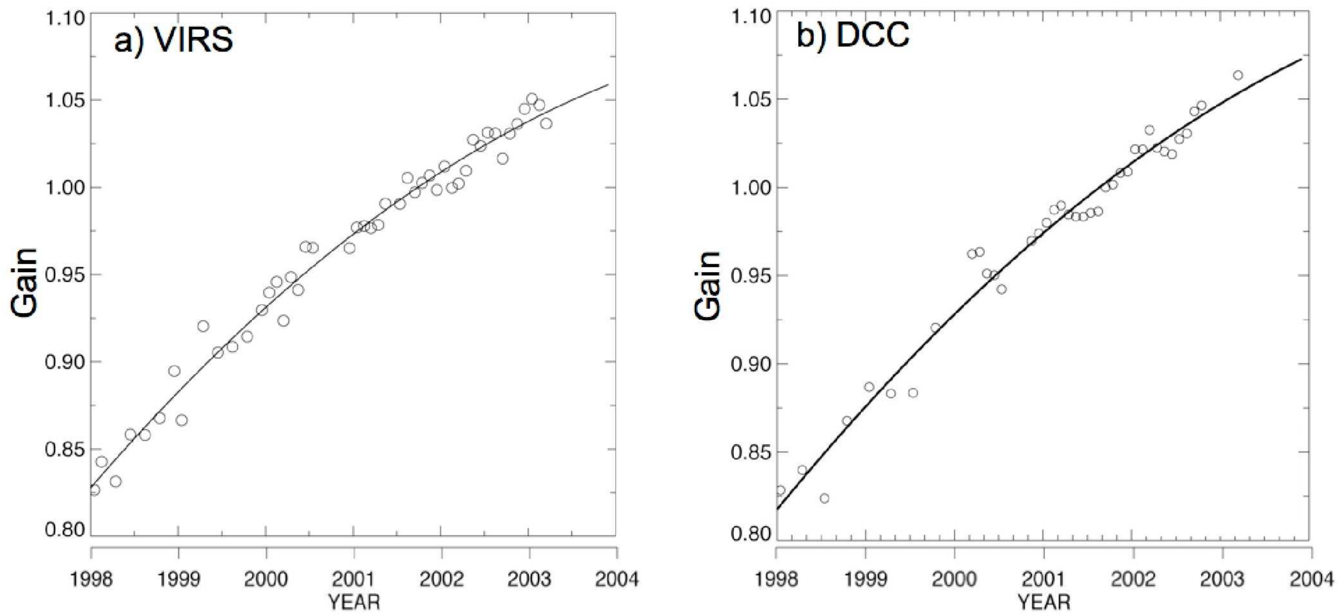

Fig. 7 Monitoring of the GOES-8 visible (0.63µm) channel using the DCC and LEO/GEO inter-calibration methods. The left panel (a) shows the GOES-8 visible gain during 1998 through 2003, based on the inter-calibration of VIRS and GOES-8. The right panel (b) shows the relative DCC calibration, normalized to the VIRS/GOES-8 gain on January 2001, based on the degradation of the DCC visible digital counts over time. A 2^{nd} order regression is also plotted for each method. Note the excellent agreement between the two calibration methods.

8.

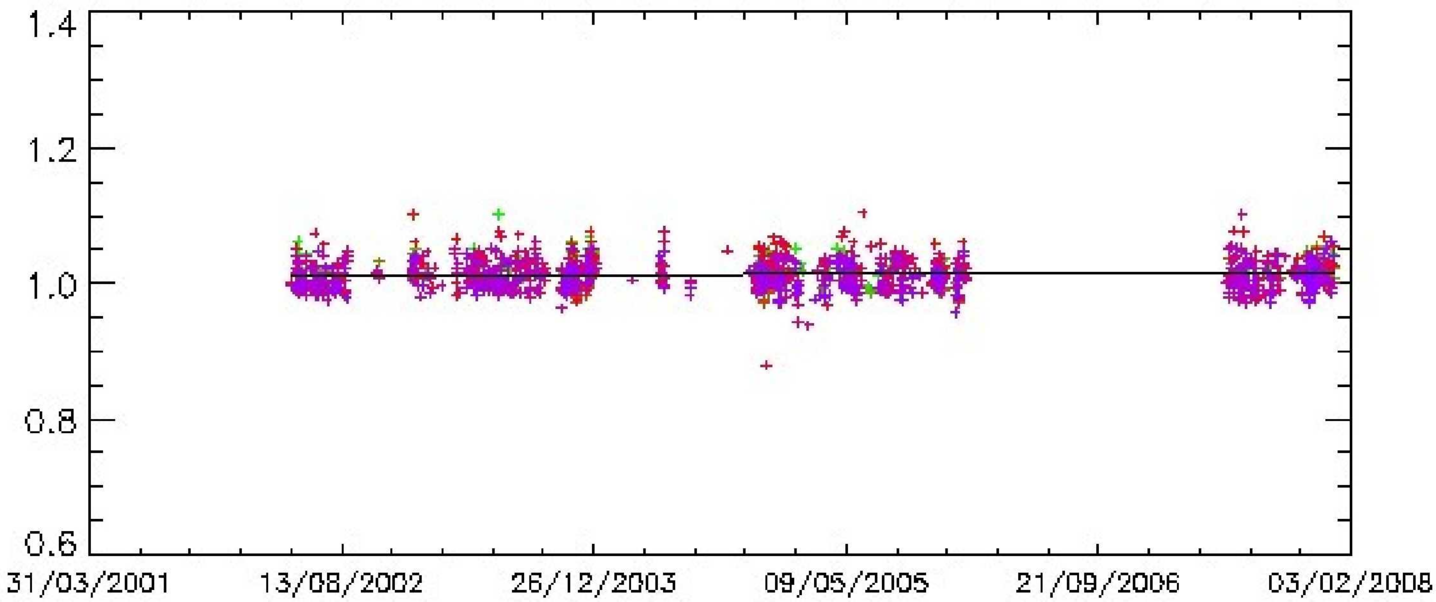

Fig. 8. Time series of the ratio of the ESA MERIS to NASA MODIS 0.665 μm visible channel reflectance from observations at 19 desert sites in North Africa and Saudi Arabia. The results show very good agreement and stability between the two sensors.

9.

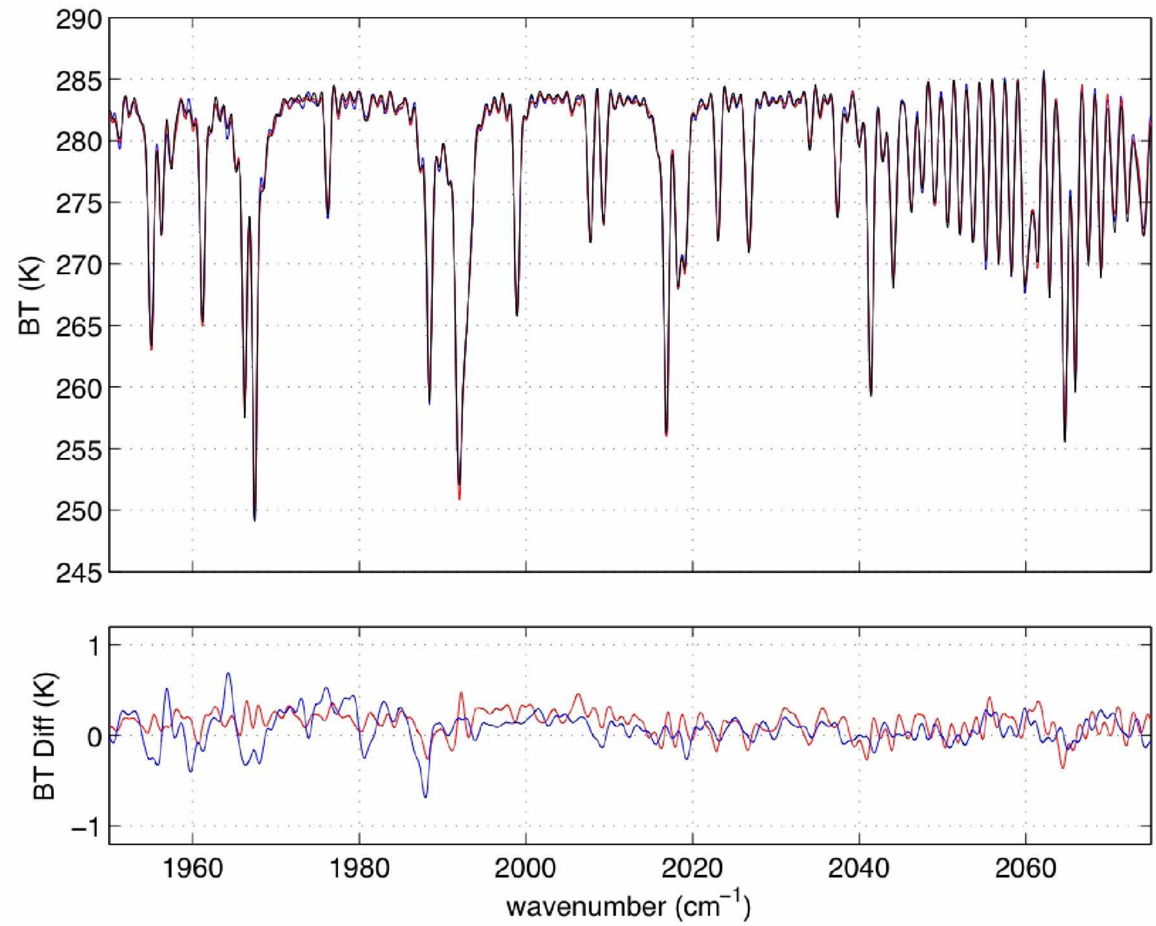

Fig. 9. Validation of IASI observations for clear sky conditions using S-HIS and NAST-I observations from a high altitude aircraft underflight on 19 April 2007 over the Oklahoma ARM site. The top panel shows S-HIS (red), NAST-I (blue), and IASI (black) mean brightness temperature (BT) spectra reduced to S-HIS spectral resolution; the bottom panel shows IASI minus S-HIS (red) and IASI minus NAST-I (blue) differences, with maximum channel by channel differences on the order of 0.1 to 0.2 K.

10.

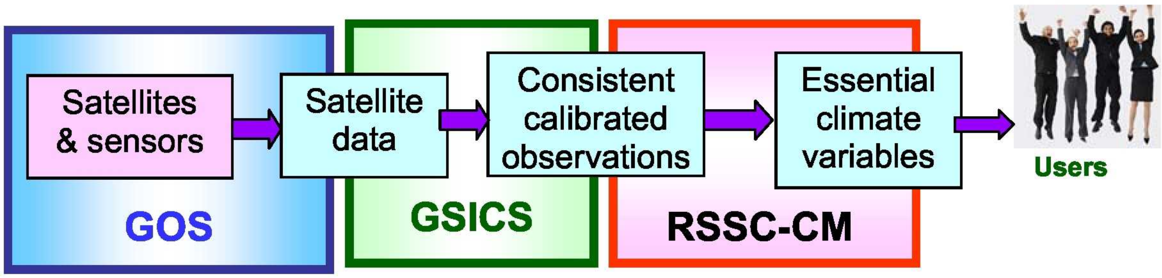

Fig. 10. The role of GSICS in the end-to-end process of creating satellite-based climate data records operationally at the WMO's Regional/Specialized Satellite Centers (R/SSC) for Climate Monitoring from observations of the satellite component of the Global Observing System (GOS).